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LATERAL HEAT FLOW EFFECTS ON THERMOGRAPHIC SENSITIVITY

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THE SECOND JOINT NASA/FAA/DoD
CONFERENCE ON AGING AIRCRAFT

August 31 - September 3, 1998

Williamsburg Marriott Hotel
Williamsburg VA

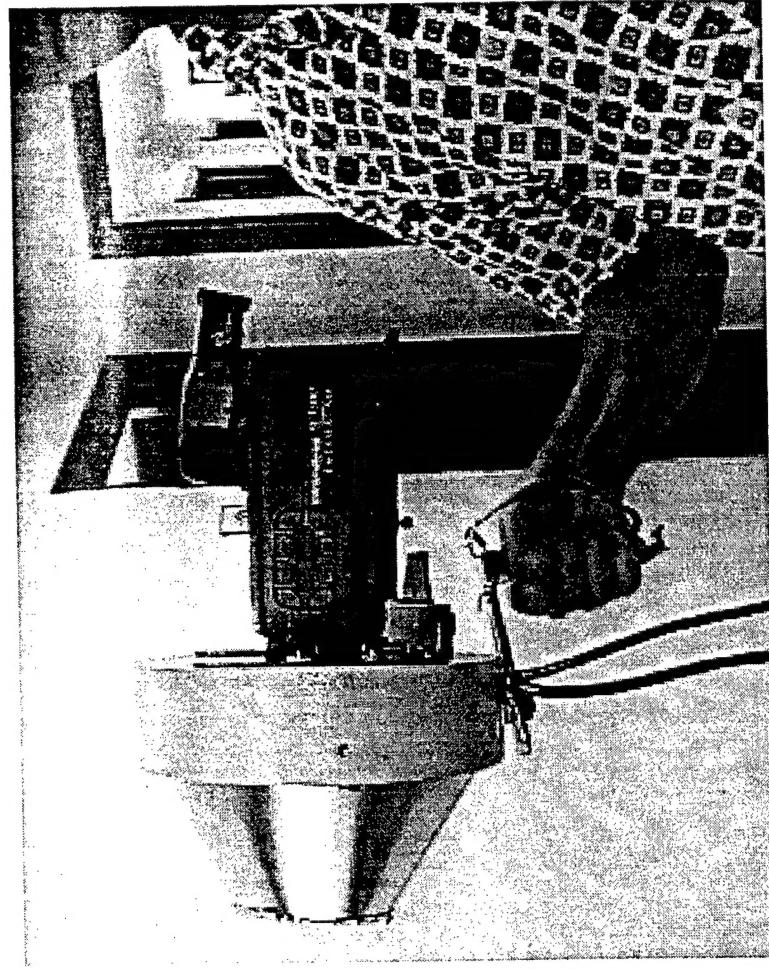
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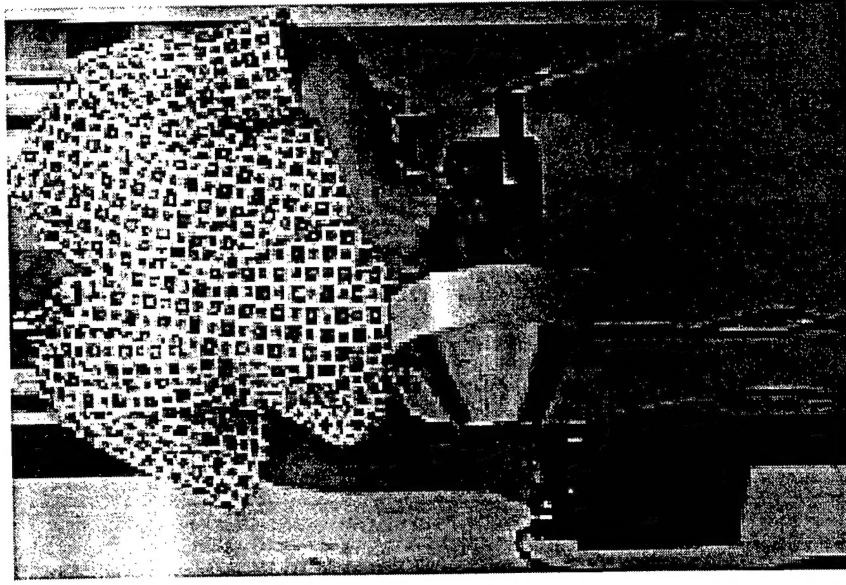
PUBLIC AFFAIRS OFFICE
NAVAL AIR SYSTEMS COMMAND

H. Howard

PORTABLE IR CAMERA SYSTEM

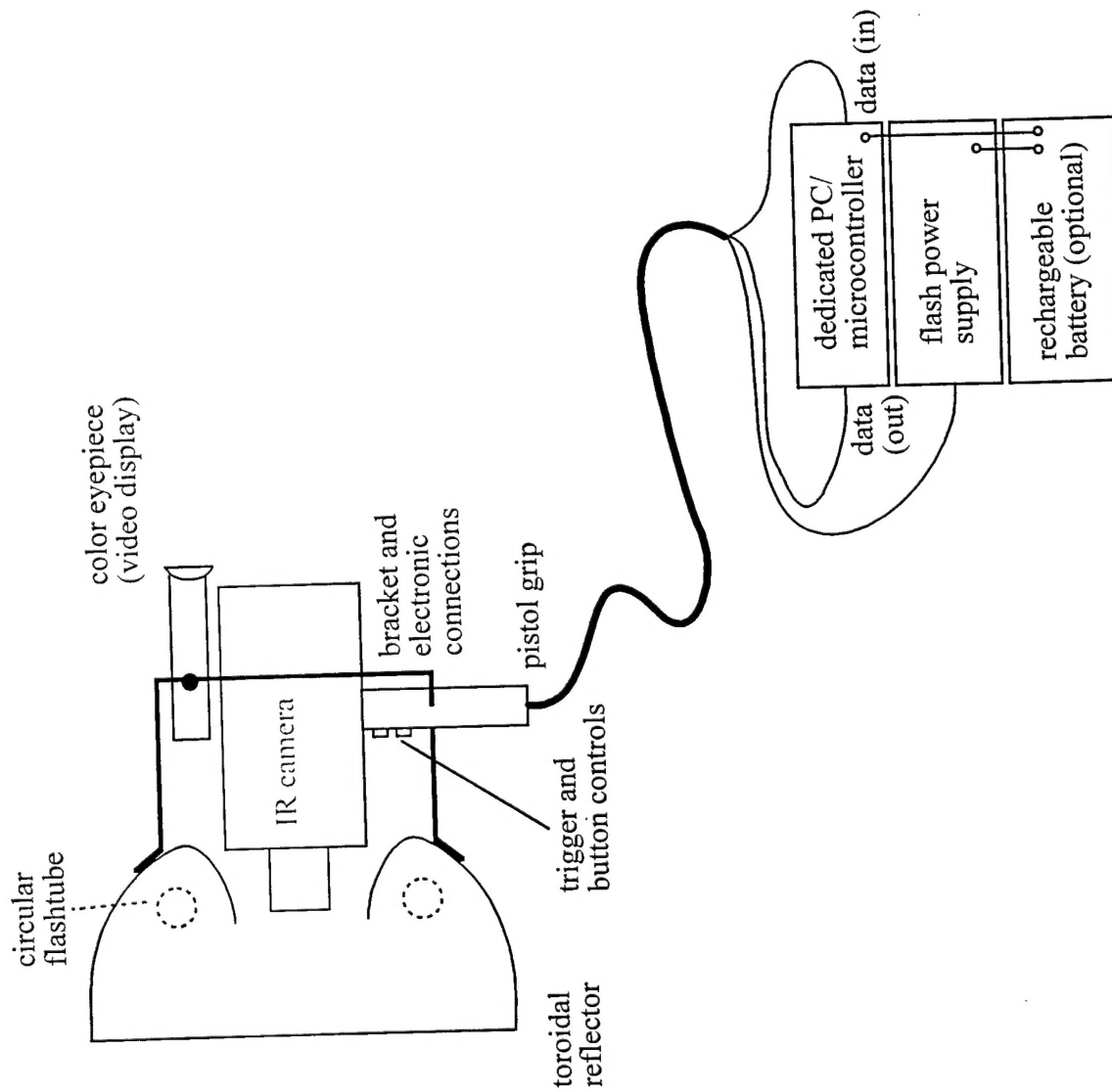


CAMERA HEAD

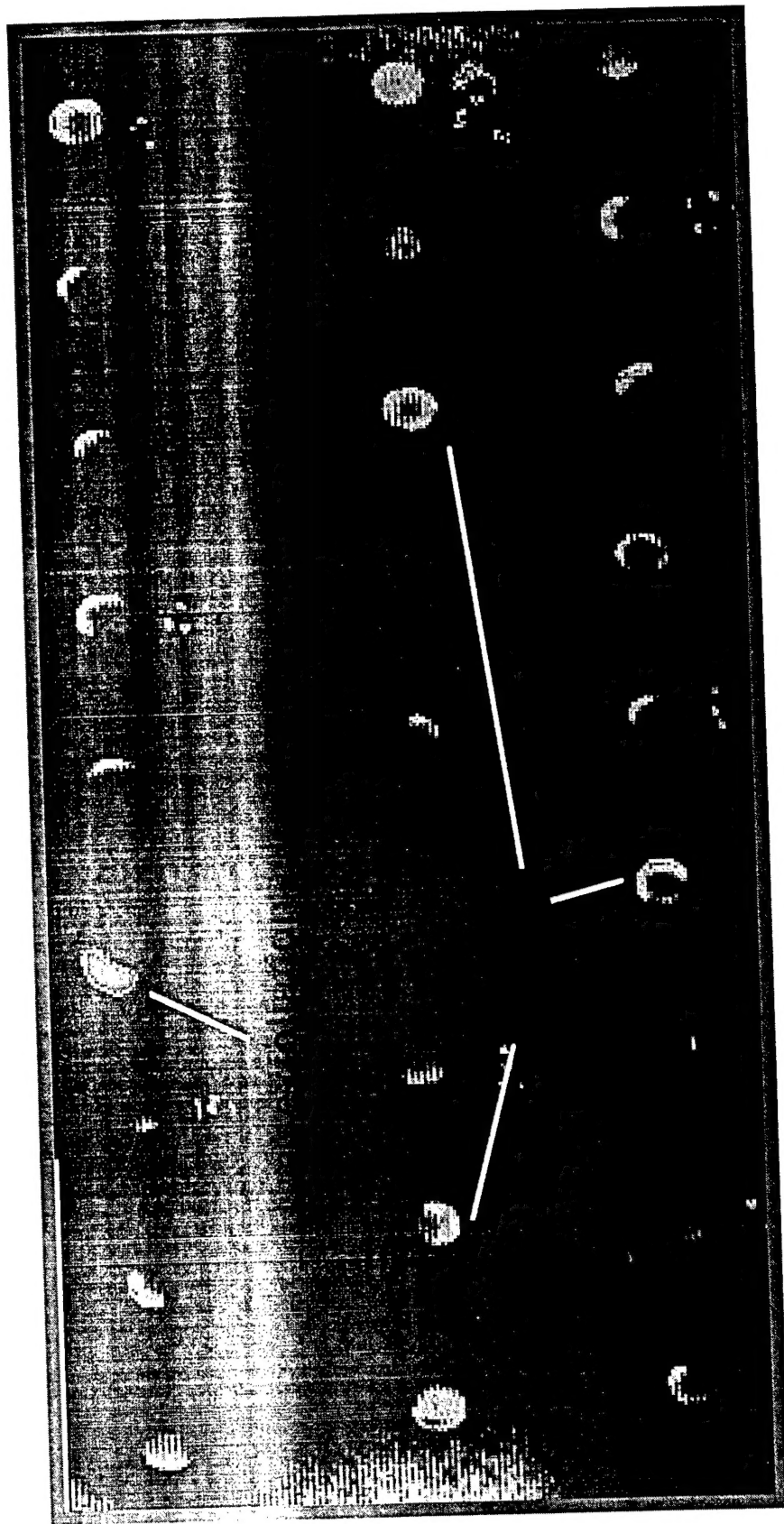


AND POWER SUPPLY

PORTABLE IR CAMERA SYSTEM

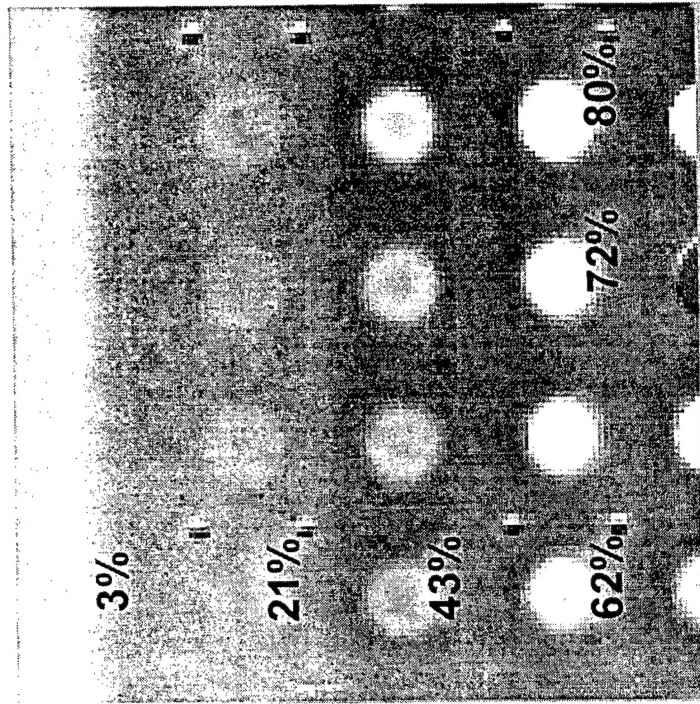


CORROSION DETECTION



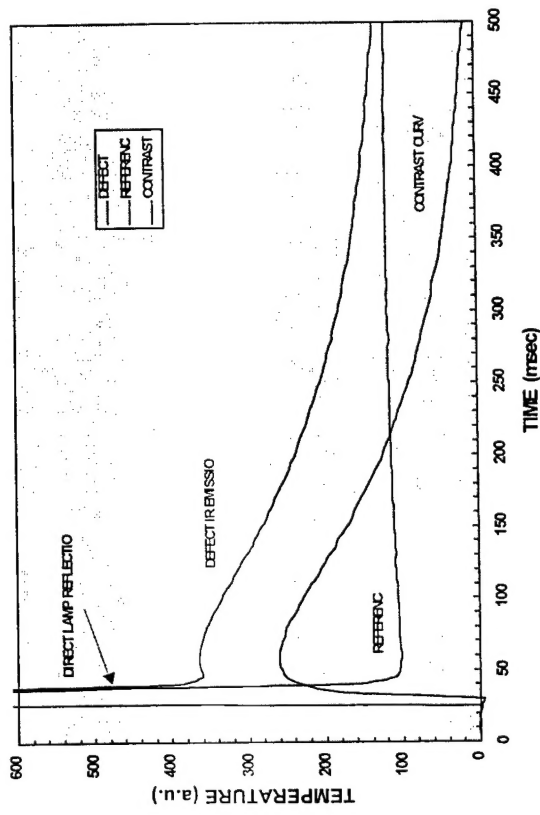
TEST PANEL & TYPICAL TIME-RESPONSE CURVES

1/8" Thick Al-7075 panel

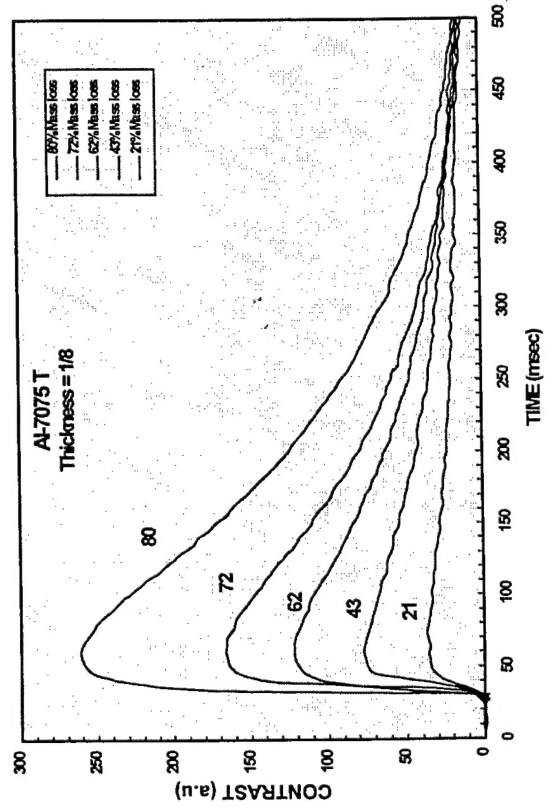


1" Diameter Holes

TEMPERATURE TIME SEQUENCE



CONTRAST CURVE

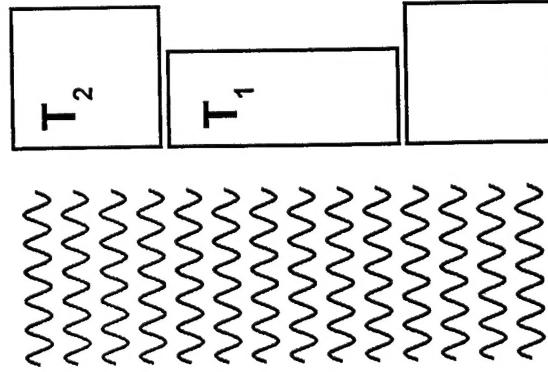
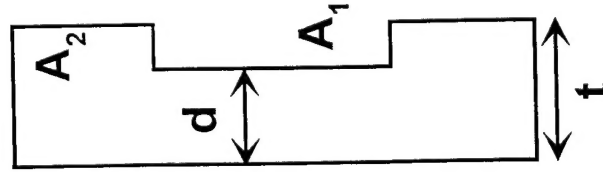


NO LATERAL HEAT CONDUCTIVITY APPROXIMATION

FLAT
BOTTOM
HOLE

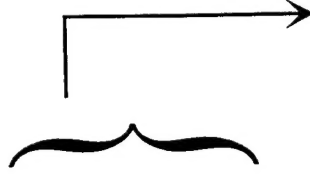
NO LATERAL
CONDUCTION
APPROXIMATION

$$q = m \cdot c \cdot \Delta T$$



$$q_2 = \rho \cdot A_2 \cdot t \cdot c \cdot T_2$$

$$q_1 = \rho \cdot A_1 \cdot d \cdot c \cdot T_1$$



$$\Delta T = \frac{Q}{\rho \cdot c} \left(\frac{1}{d} + \frac{1}{t} \right)$$

$$\Delta T = T_1 - T_2$$

$$Q = q/A$$

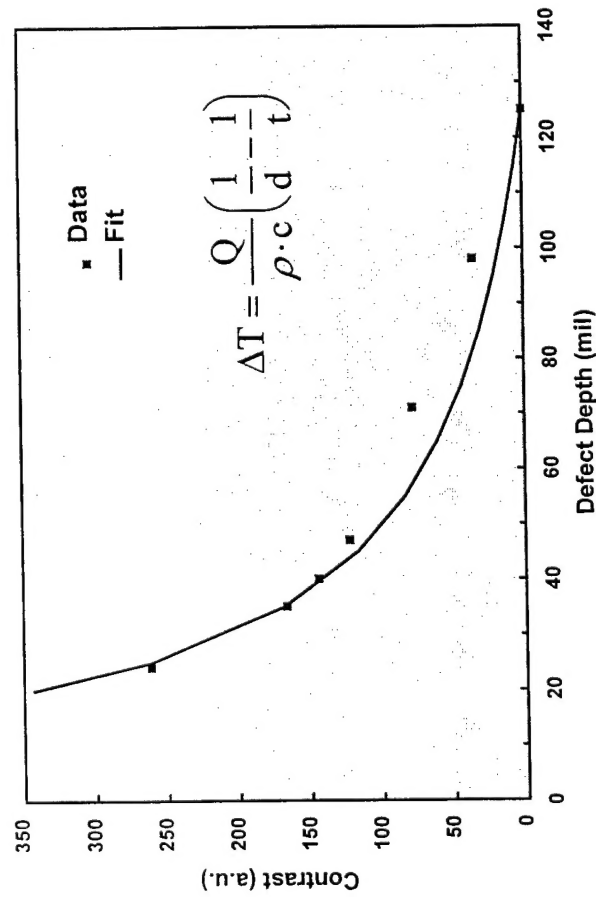
CONTRAST PROPERTIES

$$\Delta T = \frac{Q}{\rho \cdot c} \left(\frac{1}{d} - \frac{1}{t} \right)$$

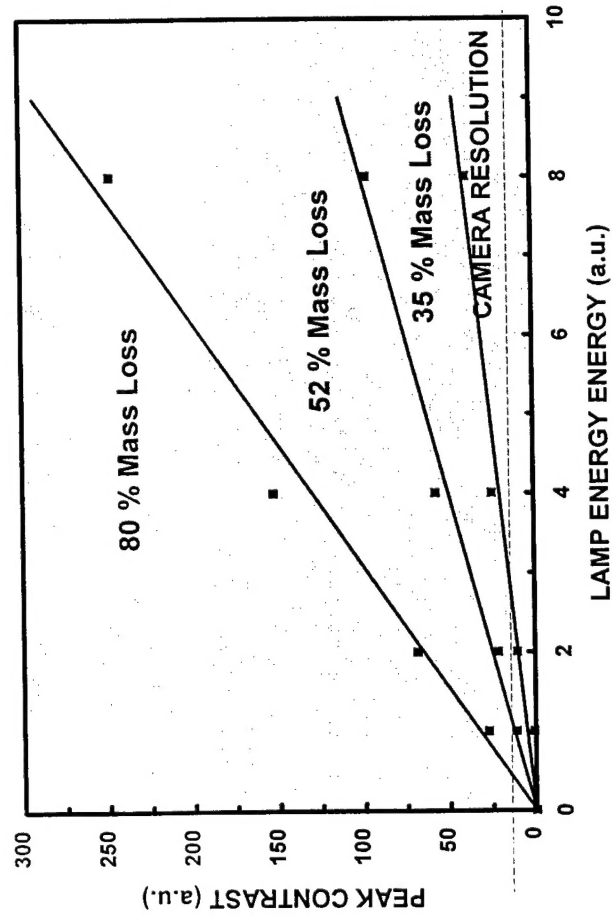
1. THE CONTRAST (ΔT) INCREASES LINEARLY WITH THE AMOUNT OF DEPOSITED ENERGY PER UNIT AREA (Q).
2. THE HIGHER THE SPECIFIC HEAT-DENSITY OF A MATERIAL ($\rho c \uparrow$) THE SMALLER THE PEAK CONTRAST ($\Delta T \downarrow$)
3. THE CLOSER THE DEFECT TO THE SURFACE ($d \rightarrow 0$) THE HIGHER THE PEAK CONTRAST ($\Delta T \rightarrow \infty$).
4. AS THE DEFECT DEPTH APPROACHES THE PANEL THICKNESS ($d \rightarrow t$) THE CONTRAST VANISHES ($\Delta T \rightarrow 0$).
5. FOR A GIVEN DEFECT DEPTH D , THE THICKER THE PANEL ($t \rightarrow \infty$) THE LARGER THE CONTRAST ($\Delta T \rightarrow Q/\rho c d$).

SIMPLE MODEL CORRELATION (no lateral heat flow)

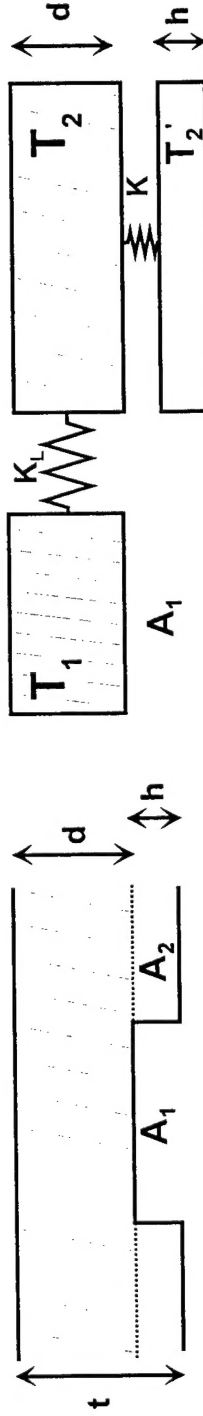
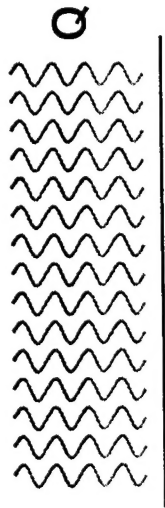
CONTRAST vs DEPTH



DEPTH OF RESOLUTION vs ENERGY



LATERAL HEAT FLOW MODEL



$$\rho \cdot A_1 \cdot d \cdot c \cdot \frac{dT_1}{dt} = k_L \cdot \frac{A_L}{R} (T_2 - T_1)$$

$$\rho \cdot A_2 \cdot d \cdot c \cdot \frac{dT_2}{dt} = k_L \cdot \frac{A_L}{R} (T_1 - T_2) + k \cdot \frac{A_2}{d+h} (T_2' - T_2)$$

$$\rho \cdot A_2 \cdot h \cdot c \cdot \frac{dT_2'}{dt} = k \cdot \frac{A_2}{d+h} (T_2 - T_2')$$

k = Thermal Conductivity

k_L = Lateral Thermal Conductivity

LATERAL HEAT FLOW EFFECTS

$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \left(e^{-\frac{a}{d(d+h)} \rho c t} - e^{-\frac{l+r}{d(d+h)} \rho c t} \right)$$

$$t_{\max} = \frac{\rho c}{k} \frac{d \cdot t_o}{1 - a + r} \ln \frac{1+r}{a}$$

$$\Delta T_{\max} = \frac{Q}{\rho c} \left(\frac{1}{d} - \frac{1}{t_o} \right) \cdot \left(\frac{a \cdot h}{t_o} \right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$

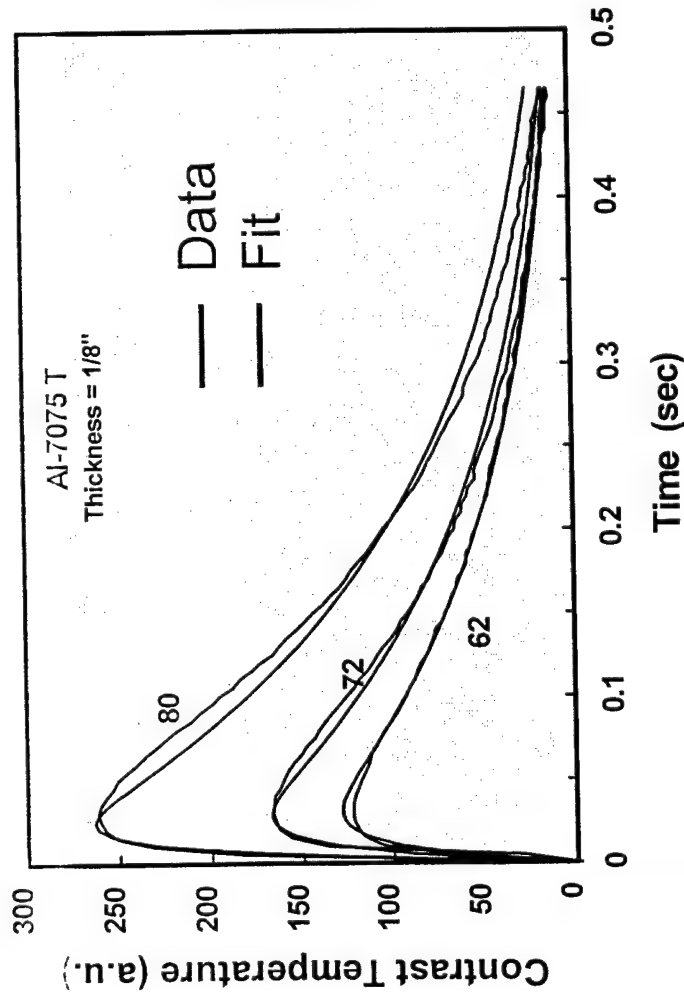
$$a = \frac{k_L}{k} \frac{A_L}{A} \frac{d+h}{R}$$

$$r = \frac{d}{h}$$

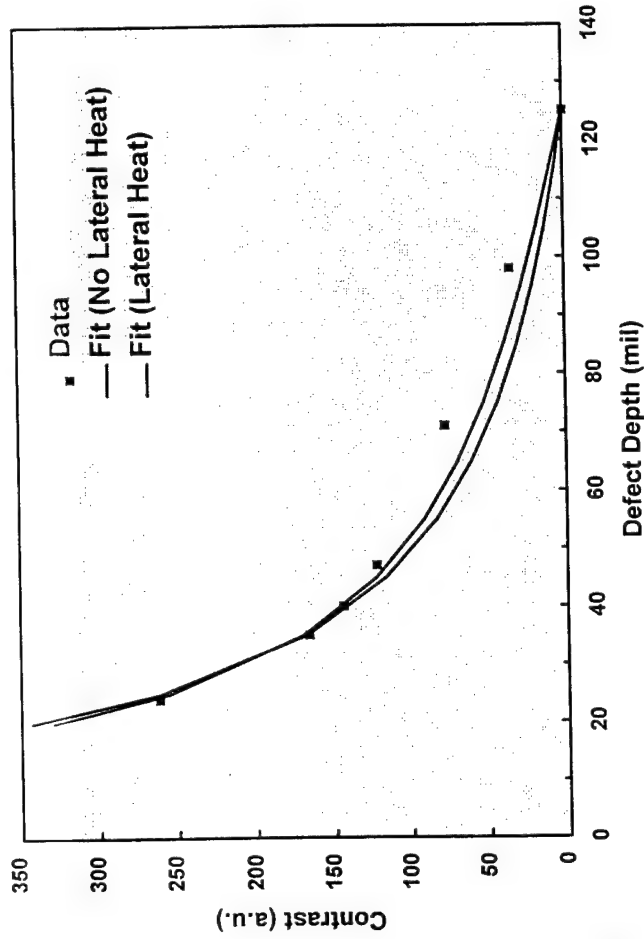
**LATERAL HEAT
 FACTOR**

THERMAL CONTRAST PREDICATIONS

Fit of Contrasts Curves



CONTRAST vs DEPTH

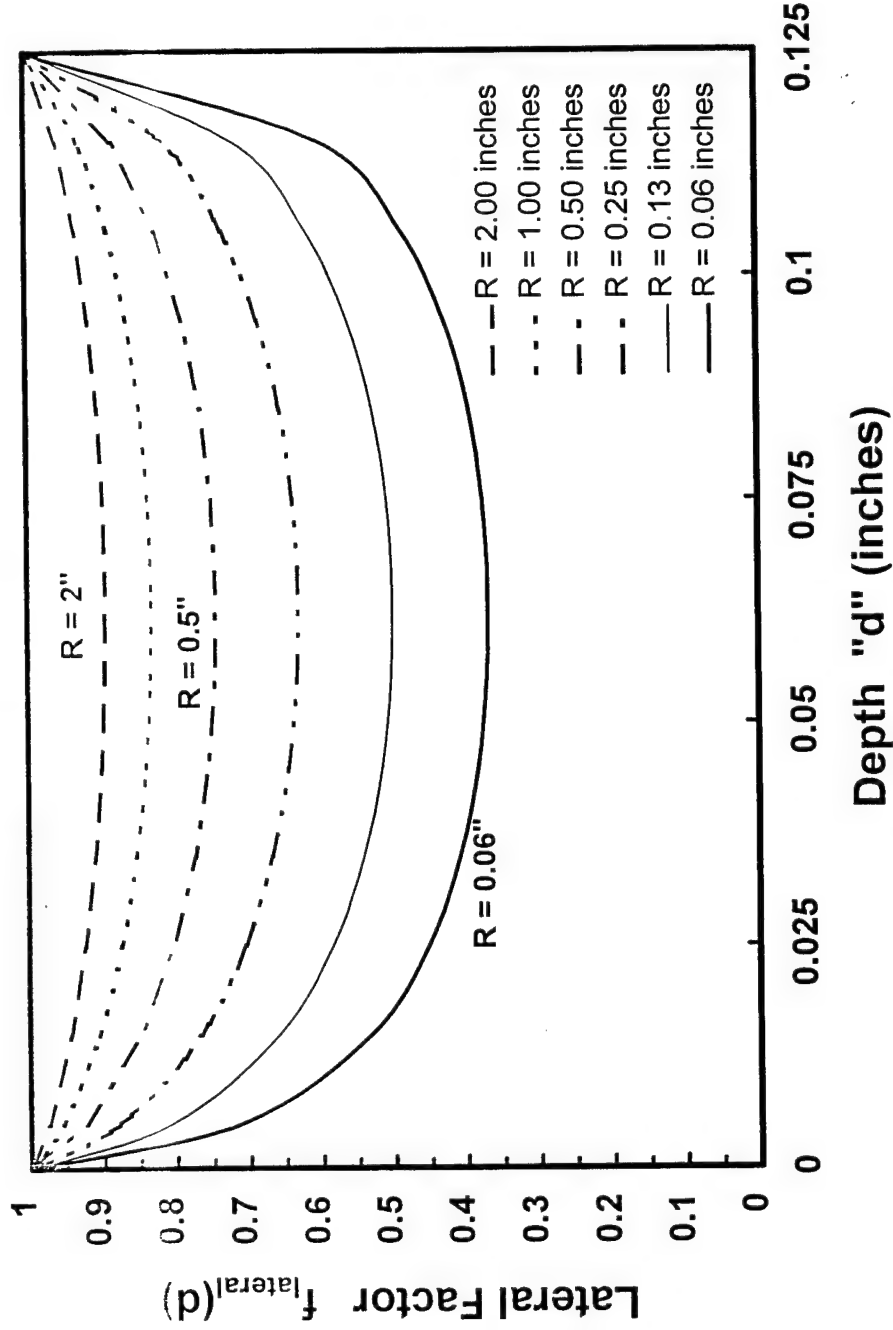


$$\Delta T(t) = \frac{Q}{\rho c \cdot d \cdot (1 - a + r)} \left(e^{-\frac{a}{d(d+h)} \rho c t} - e^{-\frac{l+r}{d(d+h)} \frac{k}{\rho c} t} \right)$$

$$\Delta T_{\max} = \frac{Q}{\rho c} \left(\frac{1}{d} - \frac{1}{t_o} \right) \cdot \left(\frac{a \cdot h}{t_o} \right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$

LATERAL HEAT FACTOR (effective contact conductivity model)

Lateral Heat Factor



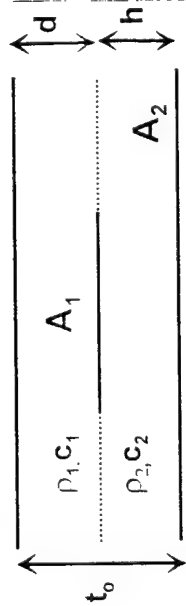
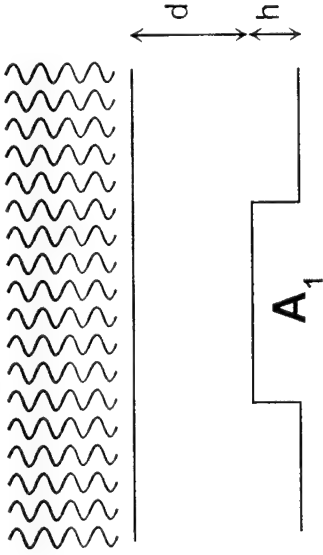
$$\Delta T_{max} = \frac{Q}{\rho c} \left(\frac{1}{d} - \frac{1}{t_o} \right) \cdot \left(\frac{a \cdot h}{t_o} \right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$



OTHER MODELING RESULTS



$$Q = J \cdot A \cdot t$$



$$\Delta T(t) = \frac{Q}{\rho_1 c_1} \cdot \frac{r_1}{d(r_1 + b \cdot r_1 r_2 - a_1)} \cdot \left(e^{-\frac{a_1 k}{Rd \rho_1 c_1} t} - e^{-\frac{r_1(1+br_2)k}{Rd \rho_1 c_1} t} \right)$$

$$\Delta T_{\text{peak}} = Q \cdot \left(\frac{1}{d} - \frac{1}{t_o} \right) \frac{\rho_2 c_2}{\rho_1 c_1} \frac{d+h}{(d\rho_1 c_1 + h\rho_2 c_2)} \cdot \left[\frac{a_1}{r_1(1+br_2)} \right]^{1-\frac{a_1}{r_1(1+br_2)}}$$

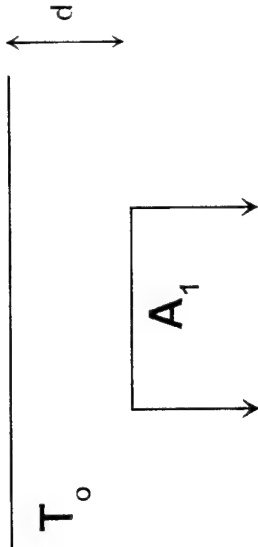
$$a_1 = \frac{k_L A_d}{k A} \quad a_2 = \frac{k_L A_h}{k A}$$

$$r_1 = \frac{R}{d+h} \quad r_2 = \frac{d}{h} \quad b = \frac{\rho_1 c_1}{\rho_2 c_2}$$

$$\Delta T(t) = \frac{J}{a \cdot k} \frac{d+h}{(1+r)(1+r-a)} \cdot \left\{ (1+r) \left(1 - e^{-\frac{a k}{d(d+h) \rho c} t} \right) - a \left(1 - e^{-\frac{1+r k}{d(d+h) \rho c} t} \right) \right\}$$

$$\Delta T(t \rightarrow \infty) = \frac{J}{a \cdot k} \cdot h$$

$$a = \frac{k_L A_L}{k A} \frac{d+h}{R} \quad r = \frac{d}{h}$$



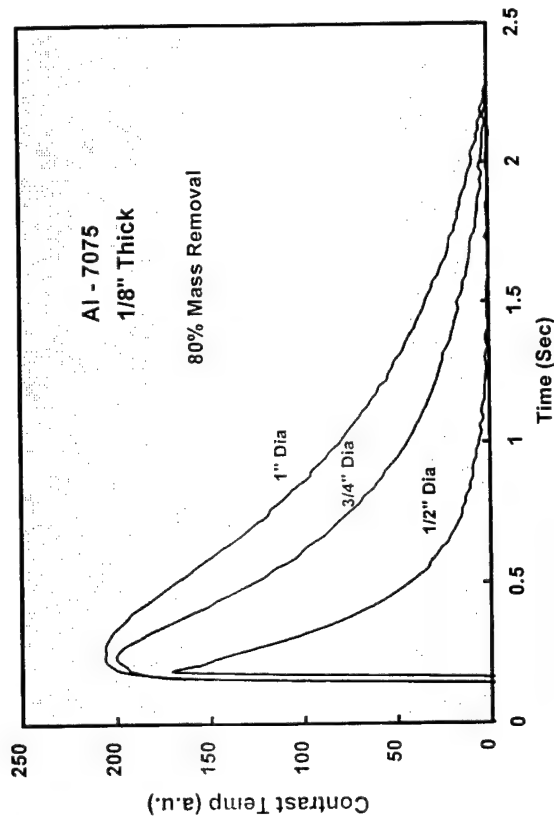
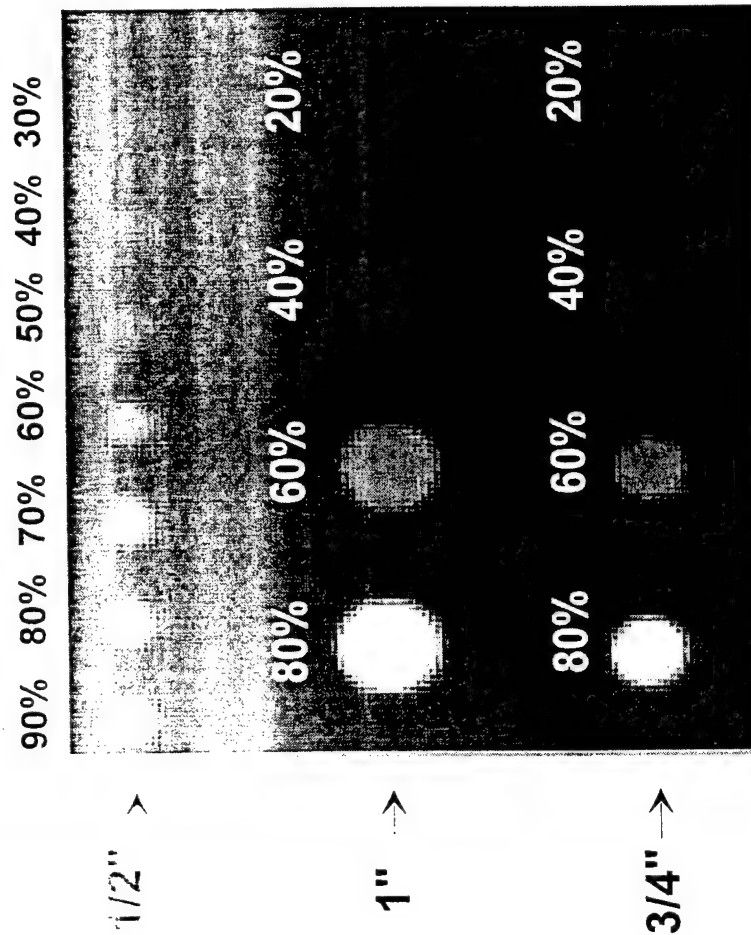
$$\Delta T(t) = \frac{Q}{\rho c} \frac{kR}{d(AkR + A_d k_1 d)} \left(e^{-\frac{b k}{d^2 \rho c} t} - e^{-\frac{1 k}{d^2 \rho c} t} \right)$$

$$\Delta T_{\text{peak}} = \frac{Q}{\rho c} \frac{kR(b-1)}{d(dA_d k_1 + R A k)} \cdot [b]^{1-b}$$

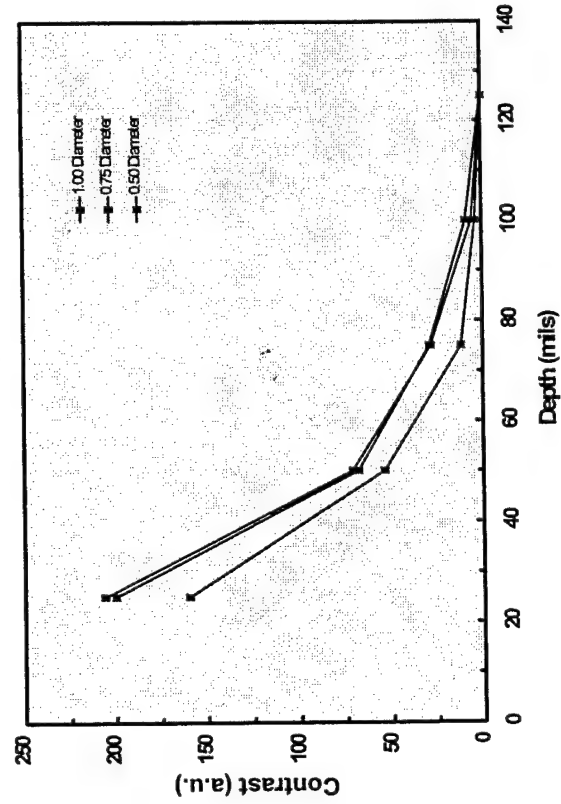
$$t_{\text{peak}} = \frac{\rho c}{k} \frac{d^2}{b-1} \ln b$$

$$b = \frac{k_1 A_d}{k A_1} \frac{d}{R}$$

EXPERIMENTAL DATA (80% mass removal)



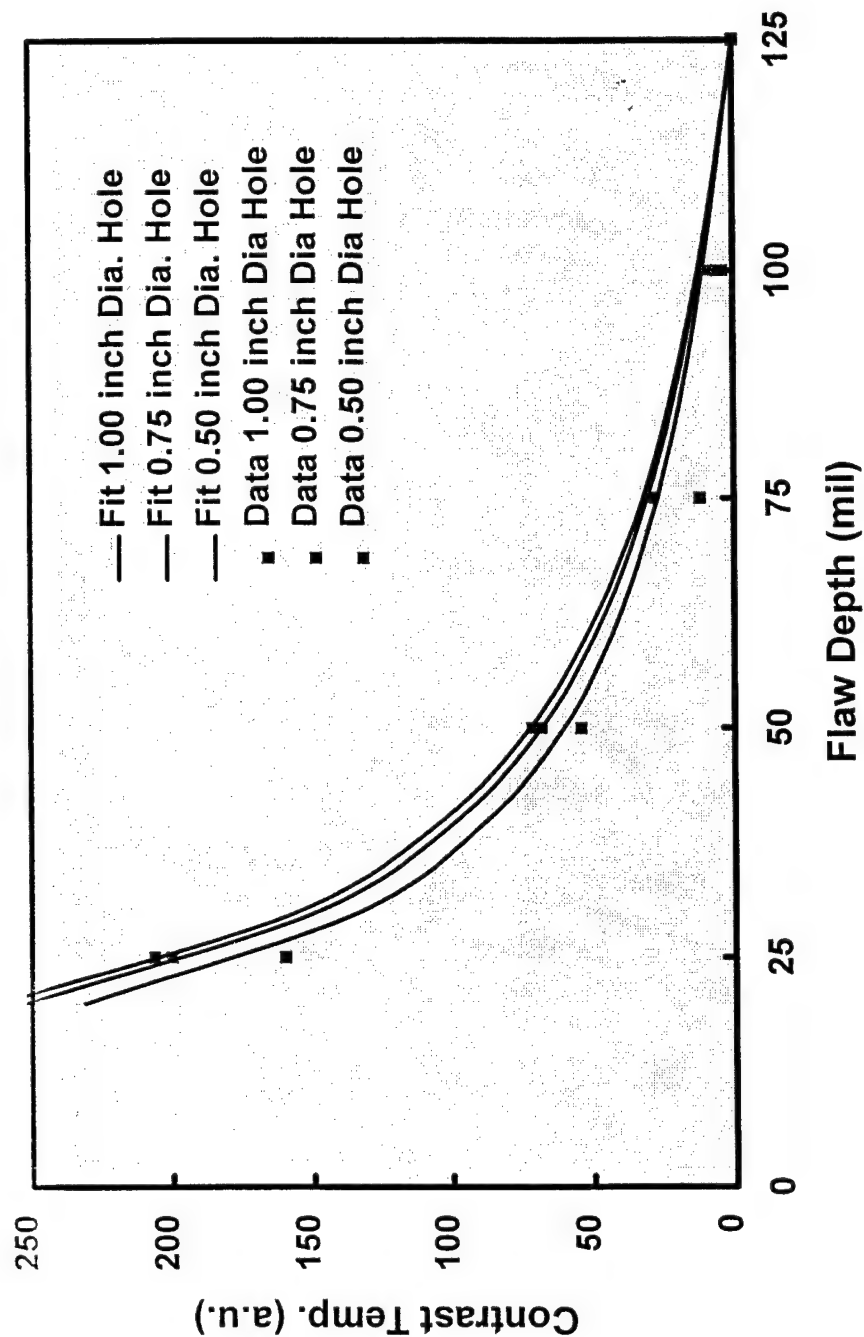
PEAK TEMP. vs DEPT



MODEL CORRELATION (effects of defect size)

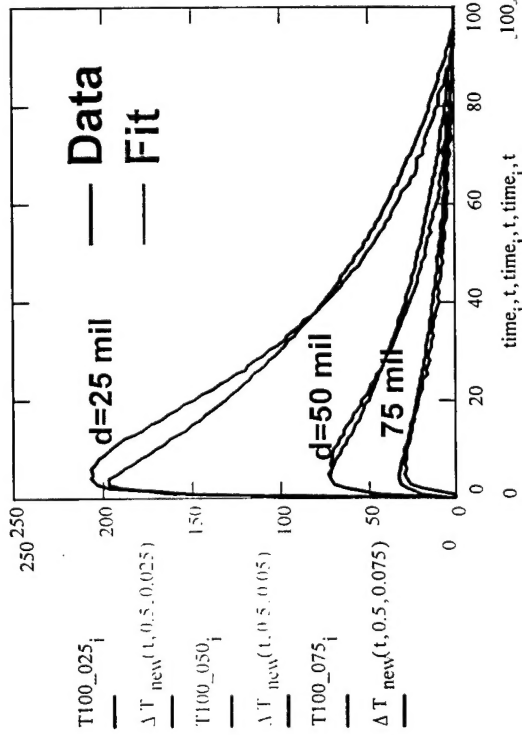
$$\Delta T_{\max} = \frac{Q}{\rho c} \left(\frac{1}{d} - \frac{1}{t_o} \right) \cdot \left(\frac{a \cdot h}{t_o} \right)^{\frac{1}{\frac{t_o}{a \cdot h} - 1}}$$

Effects of Radii

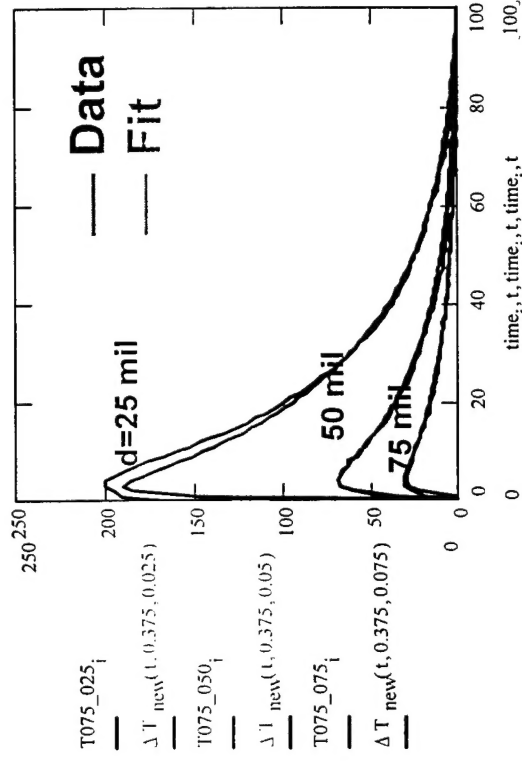


MODEL TIME-RESPONSE PREDICTIONS (varying defect sizes and locations)

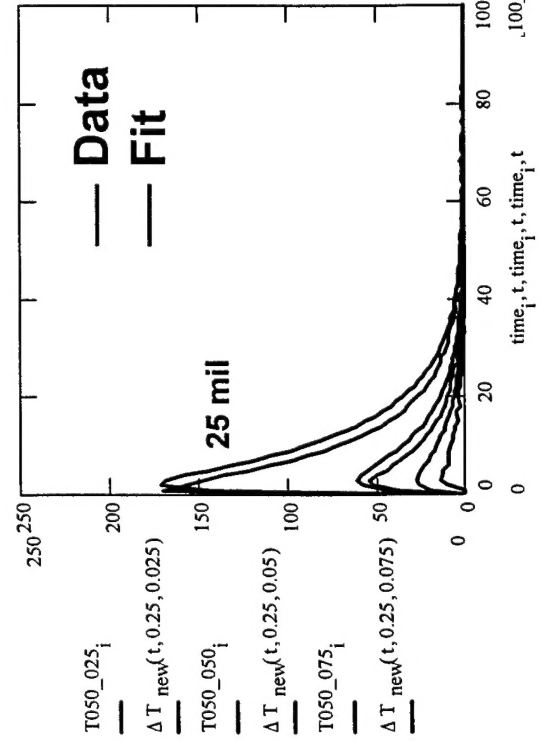
Dia = 1.00"



Dia = 0.75"



Dia = 0.50"



$$\Delta T(t) = \frac{Q}{\rho_c \cdot d \cdot (1 - a + r)} \times \left(e^{-\frac{a}{d(d+h)} \rho_c t} - e^{-\frac{1+r}{d(d+h)} \rho_c t} \right)$$

GRAPHITE EPOXY COMPOSITE PANEL

t = 117 mil

d = 48 mil

d = 61 mil



← **1/2" dia**

31 mil

41 mil

52 mil

62 mil



← **1/4" dia**

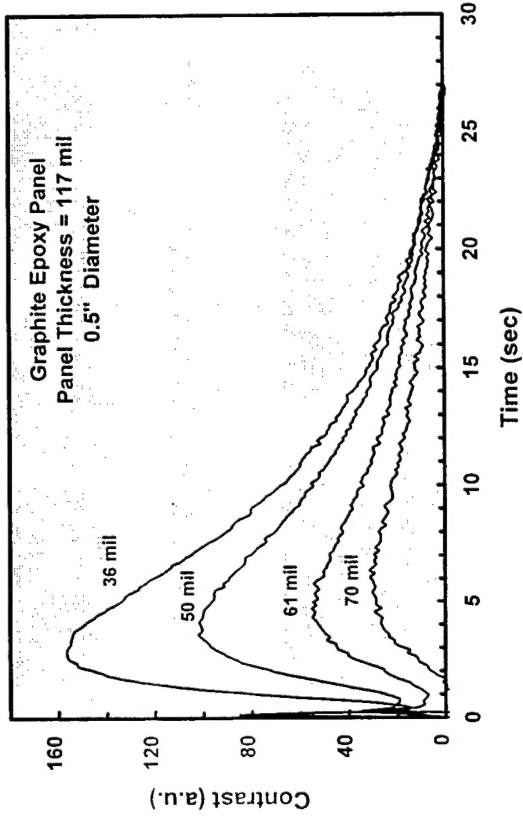


← **1/2" dia**

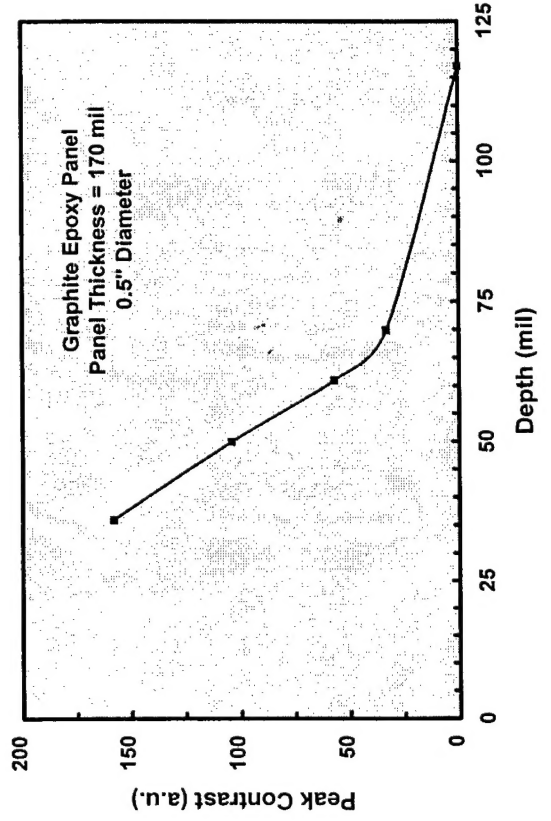
d = 36 mil

d = 70 mil

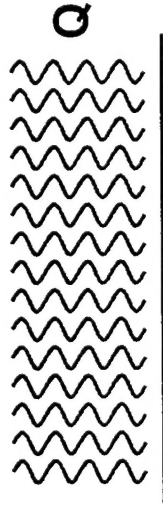
CONTRAST vs TIME



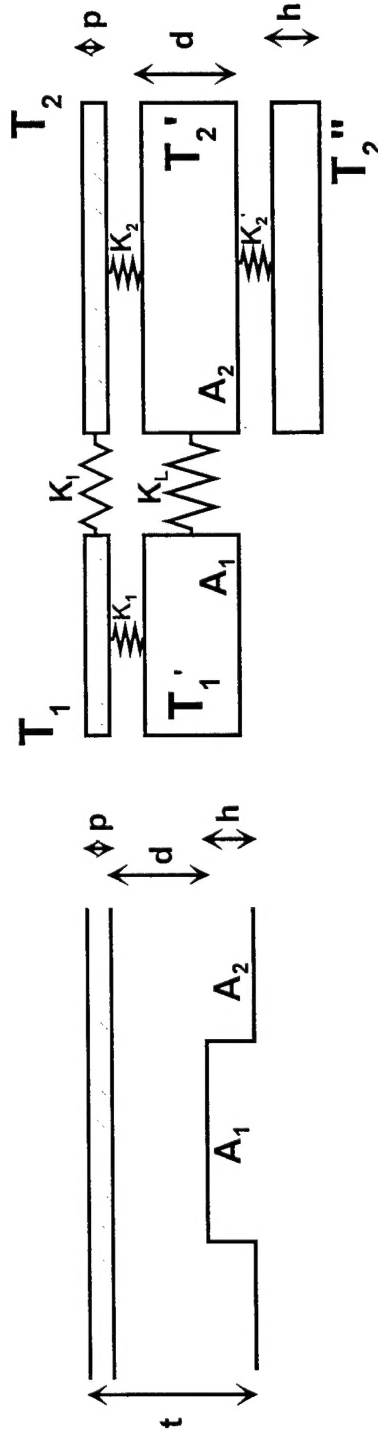
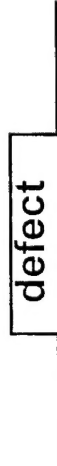
PEAK CONTRAST vs DEPTH



SIMPLE FINITE ELEMENT APPROXIMATION



Sample



$$\rho \cdot A_1 \cdot p \cdot c \cdot \frac{dT_1}{dt} = k \cdot A_1 (T_1' - T_1) + k_L \cdot A_p (T_2 - T_1)$$

$$\rho \cdot A_2 \cdot p \cdot c \cdot \frac{dT_2}{dt} = k \cdot A_2 (T_2' - T_2) + k_L \cdot A_p (T_1 - T_2)$$

...

$$\rho \cdot A_2 \cdot h \cdot c \cdot \frac{dT_2''}{dt} = k \cdot A_2 (T_2' - T_2'')$$

k = Effective Contact Normal Thermal Conductivity

k_L = Effective Contact Lateral Thermal Conductivity

FITTING RESULTS

GRAPHITE EPOXY COMPOSITE

117 mil Thick

